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CALCULATED EFFECTIVE THERMAL CONDUCTIVITIES OF HONEYCOMB SANDWICH PANELS

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SUMMARY

The steady-state temperature distribution through honeycomb-type sandwich panels is calculated with simultaneous radiation and conduction. Based on this temperature distribution, the heat which will be transmitted is calculated. An effective thermal conductivity is defined, and calculated results are presented in dimensionless form. The effect of heat transmission through the air in the cells is briefly considered. The calculated results are compared with available experimental results.

INTRODUCTION

Some of the current and anticipated high-performance flight vehicles employ honeycomb sandwich panels as an outer skin. In heat-transfer studies of such vehicles, the quantity of heat transferred through the panel is of importance, and a method of estimating this quantity is required.

Usually, the thermal resistance of a panel is experimentally determined from measurements of the amount of heat transmitted through the panel in a steady-state condition with fixed face temperatures. (See, for example, ref. 1.) However, the use of these experimental results is largely limited to panels identical to those tested and in the same temperature range as the test temperatures. Since it is impractical to obtain extensive test data on overall thermal conductivity of all honeycomb-core sandwiches of interest, it is desirable to have a means of estimating this property.

General equations for the transfer of heat in sandwich panels are developed in reference 2. In the present paper those equations are modified to permit the calculation of the steady-state temperature distribution due to simultaneous conduction and radiation through square-cell sandwich panels with given face temperatures. The equations are solved for a range of face temperatures, and effective thermal conductivities (defined not to include the effect of heat transfer through the air contained in the cells) are presented. An estimate of the effect of heat transfer through the air contained in the cells is given, and an overall thermal conductivity which includes this effect is defined. This overall thermal conductivity is compared with experimentally measured values.

SYMBOLS

ΔA solidity of core, ρ_c/ρ

$F_{m,n}$ overall configuration factors

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h height of core (not total thickness of panel)

k thermal conductivity of core material

k_A thermal conductivity of air

k_E effective thermal conductivity due to radiation and conduction (defined by eq. (6))

K overall thermal conductivity, $k_A + k_E$

Q total heat transmitted through sandwich

Q_A heat transmitted through panel by air

Q_5 net heat flux at position 5 (does not include Q_A)

S length of a side of a cell

T absolute temperature unless specified otherwise

$\bar{T}$ dimensionless absolute temperature, $\left(\frac{\sigma\epsilon h}{3k\ \Delta A}\right)^{1/3} T$

x distance from heated face

ϵ emissivity

ρ density of core material

ρ_c core density

σ Stefan-Boltzmann constant, $0.174 \times 10^{-8} \dfrac{\text{Btu}}{\text{ft}^2\text{-hr-}(^{\circ}\text{R})^4}$

Subscripts:

m,n integers from 1 to 5

ANALYSIS

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If an effective thermal conductivity which includes the effects of all modes of heat transfer can be determined for a honeycomb sandwich panel whose faces are at different constant temperatures, the amount of heat that is transmitted through the panel can be calculated. Since cellular air spaces exist in such panels, it is necessary to consider radiation between surfaces and convection or conduction through the air as well as conduction through the walls of the cells.

The determination of the effective conductivity is complicated by the fact that, in general, the heat transferred by any mode is a nonlinear function of temperature and all the modes of heat transfer are interrelated. However, the amount of heat transferred by the air is usually small and can be treated as independent of the other modes. With this simplification, the general equations for the transfer of heat by radiation and conduction in honeycomb-type sandwich panels are derived in reference 2. These equations are expanded into finite-difference equations about the points $\frac{x}{h} = 0, 1/6, 1/2, 5/6,$ and 1 in the reference. (See fig. 1.) In the finite-difference form, these equations are readily adaptable to the present case.

The following assumptions will be made in the analysis of conduction and radiation:

1. Thermal properties are considered constant at a value corresponding to the mean temperature of the panel.

2. Reradiation is negligible; that is, all radiant energy incident on a surface is absorbed.

3. Thermal resistance is confined to the core; that is, the faces are at uniform temperature.

4. The cells have square cross section.

5. Effects of conduction and convection through the air in the cells are considered independently of conduction through the metal and radiation between metallic parts.

Unless stated otherwise only those cases in which the emissivities of the core and faces are equal will be considered. Also, if the resistance to heat flow of the faces is an appreciable fraction of the total resistance of the panel (such a case might occur with nonmetallic faces and a metallic core), such resistance must be added to that calculated by the methods presented below.

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The equations governing the transfer of heat in sandwich panels given by equations (11) in reference 2 are for the case in which the temperature of one face is prescribed and the other is insulated. If both faces have constant prescribed temperatures and a steady-state condition has been reached, the temperatures in the core must satisfy the equations:

$$\left.\begin{aligned} 2T_1 - 3T_2 + T_3 - \frac{\sigma\epsilon h}{3k\ \Delta A}\sum_{m=1}^{5} F_{2,m}\left(T_2{}^4 - T_m{}^4\right) &= 0 \\ T_2 - 2T_3 + T_4 - \frac{\sigma\epsilon h}{3k\ \Delta A}\sum_{m=1}^{5} F_{3,m}\left(T_3{}^4 - T_m{}^4\right) &= 0 \\ T_3 - 3T_4 + 2T_5 - \frac{\sigma\epsilon h}{3k\ \Delta A}\sum_{m=1}^{5} F_{4,m}\left(T_4{}^4 - T_m{}^4\right) &= 0 \end{aligned}\right\} \qquad (1)$$

where $F_{n,m}$ is the fraction of the radiant flux leaving all surfaces at station n which is incident on all surfaces at station m, multiplied by the area of all the surfaces at station n. Numerical values of these overall configuration factors $F_{n,m}$ taken from reference 2, are presented in table I.

If a dimensionless temperature

$$\bar{T}_n = \left(\frac{\sigma\epsilon h}{3k\ \Delta A}\right)^{1/3} T_n \qquad (2)$$

is defined and substituted into equations (1), they become independent of $\frac{\epsilon h}{k\ \Delta A}$ and are

$$\left.\begin{aligned}
2\overline{T}_1 - 3\overline{T}_2 + \overline{T}_3 - \sum_{m=1}^{5} F_{2,m}\left(\overline{T}_2{}^4 - \overline{T}_m{}^4\right) &= 0 \\
\overline{T}_2 - 2\overline{T}_3 + \overline{T}_4 - \sum_{m=1}^{5} F_{3,m}\left(\overline{T}_3{}^4 - \overline{T}_m{}^4\right) &= 0 \\
\overline{T}_3 - 3\overline{T}_4 + 2\overline{T}_5 - \sum_{m=1}^{5} F_{4,m}\left(\overline{T}_4{}^4 - \overline{T}_m{}^4\right) &= 0
\end{aligned}\right\} \tag{3}$$

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Therefore, if $\overline{T}_1$, $\overline{T}_5$, and the cell size ratio h/S are given, equations (3) may be solved for the temperature distribution through the panel.

In order to maintain the steady-state temperature distribution given by equations (3), the same amount of heat supplied at the hot face (assumed hereafter to be the position 1) must be removed at the cold face (position 5). The net flux of heat to the cold face from the core and the hot face is given by the heat-balance equation

$$Q_5 = \frac{k\ \Delta A}{h/6}\left(T_4 - T_5\right) - \sigma\epsilon \sum_{m=1}^{4} F_{5,m}\left(T_5{}^4 - T_m{}^4\right) \tag{4}$$

Substituting the dimensionless temperature, equation (2), yields

$$Q_5 = \left(\frac{3k\ \Delta A}{\sigma\epsilon h}\right)^{1/3} \frac{k\ \Delta A}{h}\left[6\left(\overline{T}_4 - \overline{T}_5\right) - 3\sum_{m=1}^{4} F_{5,m}\left(\overline{T}_5{}^4 - \overline{T}_m{}^4\right)\right] \tag{5}$$

An effective thermal conductivity k_E is now defined such that

$$Q_5 = \frac{k_E}{h}\left(T_1 - T_5\right) \tag{6}$$

or in the dimensionless notation

$$Q_5 = \left(\frac{3k\ \Delta A}{\sigma\epsilon h}\right)^{1/3} \frac{k_E}{h}\left(\overline{T}_1 - \overline{T}_5\right) \tag{7}$$

From equations (5) and (7),

$$\frac{k_E}{k\ \Delta A} = \frac{6\left(\overline{T}_4 - \overline{T}_5\right) - 3\sum_{m=1}^{4} F_{5,m}\left(\overline{T}_5{}^4 - \overline{T}_m{}^4\right)}{\overline{T}_1 - \overline{T}_5} \tag{8}$$

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The effective thermal conductivity given by equation (8) accounts only for the heat transferred by conduction through the metallic elements and the heat transferred by radiation, and therefore must be modified to include the transfer through the air contained in the cells. Heat may be transmitted through the air in a sandwich panel by conduction and convection. Convection will depend on panel orientation and acceleration, as well as temperature distribution and thermal properties. However, if the cell size is small, it is likely that conduction will predominate. Therefore, it will be assumed that the amount of heat transmitted by convection may be neglected in comparison with that transmitted by other modes. The heat transmitted by conduction through the air may be approximated by:

$$Q_A = \frac{k_A}{h}\left(T_1 - T_5\right) \tag{9}$$

Values of k_A, the thermal conductivity of air, are given in reference 3. These values are plotted in figure 2 for temperatures to 1,200° F. For higher temperatures, the following equation may be used:

$$k_A = 1.14 \times 10^{-3} \frac{T^{3/2}}{T + 442} \tag{10}$$

where T has the units °R and k_A has the units $\frac{\text{Btu}}{\text{ft-hr-}^{\circ}\text{R}}$.

Finally, the overall thermal conductivity is defined as

$$K = k_E + k_A \tag{11}$$

RESULTS

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Calculated Effective Conductivities

Typical calculated temperature distributions through the core are presented in figure 3 for a core-height—cell-size ratio of 2. In each case the departure of the temperature from a linear distribution is caused by radiant-energy absorption in the cell walls. This departure increases as the difference between the face temperatures becomes larger. The gradient at the cold face $\frac{x}{h} = 1$ is greater than that resulting from a linear temperature distribution and can be anticipated to lead to an increase in the amount of heat transferred by conduction to the cold face.

An examination of all calculated temperature distributions for values of h/S between 0.8 and 2.0 showed that the core temperature distribution is essentially independent of h/S in this range.

A complete tabulation of $k_E/k\ \Delta A$ as a function of end temperatures $\bar{T}_1$ and $\bar{T}_5$ and of the ratio of core height to cell size h/S is presented in table II for all cases solved. Since it is not practical to calculate all values of $k_E/k\ \Delta A$ which are of interest, it is desirable to have the information available in graphical form. It can be shown from the calculated results that constant values of the sum $\bar{T}_1^{5/3} + \bar{T}_5^{5/3}$ correspond to practically constant values of $k_E/k\ \Delta A$, or

$$\frac{k_E}{k\ \Delta A} = f\left(\bar{T}_1^{5/3} + \bar{T}_5^{5/3}\right) \tag{12}$$

Figure 4 is a plot of $k_E/k\ \Delta A$ against $\bar{T}_1^{5/3} + \bar{T}_5^{5/3}$. This figure is a satisfactory representation of all the information given in table II. Because low values of $k_E/k\ \Delta A$ are likely to be of more interest than higher values, the region $\frac{k_E}{k\ \Delta A} \leqq 3$, $\bar{T}_1^{5/3} + \bar{T}_5^{5/3} \leqq 1$ is plotted to a larger scale in figure 5.

Figures 4 and 5 show that, as $\bar{T}_1^{5/3} + \bar{T}_5^{5/3}$ increases, $k_E/k\ \Delta A$ increases very rapidly and that the effective thermal conductivity can be several times that of a nonradiating panel. It can also be seen that, for a given value of $\bar{T}_1^{5/3} + \bar{T}_5^{5/3}$, $k_E/k\ \Delta A$ is decreased as h/S is increased, particularly at the larger values of the dimensionless temperature parameter. Since, as previously mentioned, the temperature distribution in the core is practically independent of h/S, the decrease in $k_E/k\ \Delta A$ must be due to reduced direct radiation to the colder face.

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Typical Use of Results

If the face temperatures, the core-material properties, and the geometry of the core are known, the effective thermal conductivity can be obtained from figure 4, or figure 5, by calculating the dimensionless temperatures $\bar{T}_1$ and $\bar{T}_5$ from equation (2):

$$\bar{T}_n = \left(\frac{\sigma \epsilon h}{3k\ \Delta A}\right)^{1/3} T_n$$

In this equation, h is the height of the core, not the thickness of the sandwich panel. The solidity ΔA is given by the ratio ρ_c/ρ, where ρ_c is the core density and ρ is the density of the material of which the core is made. The conductivity k may be taken to be the conductivity of the core material at the average temperature of the panel. In general, the emissivity will not be known with great precision. At best, it varies with surface finish and temperature. In sandwich panels the surface will be to some extent covered with the bonding or brazing material used to attach the faces of the panel to the core. However, if ϵ is between 0.7 and 0.9, the use of $\epsilon = 0.8$ will lead to errors in $\bar{T}_n$ of less than ± 4 percent.

For example, assume that an estimate is required of the effective thermal conductivity of a stainless-steel honeycomb sandwich which has a core with the following properties:

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$$h = 0.04 \text{ ft}$$

$$S = 0.02 \text{ ft}$$

$$\Delta A = 0.02$$

and further assume that

$$T_1 = 1{,}000^{\circ} \text{ R}$$

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$$T_5 = 600^{\circ} \text{ R}$$

$$k = 10 \frac{\text{Btu}}{\text{ft-hr-}^{\circ}\text{R}}$$

$$\epsilon = 0.7$$

When the above quantities are substituted into equation (2), the following relation is obtained:

$$\overline{T}_n = 0.432 \frac{T_n}{1{,}000}$$

from which

$$\overline{T}_1 = 0.432$$

$$\overline{T}_5 = 0.259$$

An evaluation of the dimensionless temperature parameter gives

$$\overline{T}_1^{5/3} + \overline{T}_5^{5/3} = 0.351$$

and from figure 5

$$\frac{k_E}{k\ \Delta A} = 1.21$$

or

$$k_E = 0.242 \frac{\text{Btu}}{\text{ft-hr-}^{\circ}\text{R}}$$

The conductivity of air at the average face temperature is obtained from figure 2 and is

$$k_A = 0.021$$

The amount of heat transferred through the sandwich is

$$Q = \frac{k_E + k_A}{h}\left(T_1 - T_5\right) = 2{,}630 \ \frac{\text{Btu}}{\text{ft}^2\text{-hr}}$$

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DISCUSSION OF RESULTS

Relative Contributions of Conduction and Radiation

The contributions of heat conduction and heat radiation to $k_E/k\ \Delta A$ are given by the first and second terms, respectively, on the right side of equation (8). Both contributions are influenced by the interaction of the two modes of heat transfer. In order to evaluate the contributions of conduction, radiation, and the interaction of these modes, results from the present solution are compared with calculations for two simple heat-transfer models which neglect the interaction effects.

In the first model, the heat transferred to the colder face by conduction is assumed to be uneffected by radiation, and the temperature is assumed to vary linearly between the face temperatures. The heat transmitted to the cold face by radiation is calculated with the linear temperature distribution and is less than the corresponding heat transfer given by the present solution. The effective conductivities are determined by substituting the known temperatures and the configuration factors (table I) into equation (8) which, for a linear temperature distribution, reduces to

$$\frac{k_E}{k\ \Delta A} = 1 - \frac{3\sum_{m=1}^{4} F_{5,m}\left(\bar{T}_5^{\,4} - \bar{T}_m^{\,4}\right)}{\bar{T}_1 - \bar{T}_5} \tag{13}$$

In the second model, heat conduction is accounted for exactly as in the first model. However, the heat transferred by radiation is assumed to be that which would be transferred between the sandwich faces if the cell sides neither emit nor absorb radiation but act as perfect reflectors. The amount of heat transferred by radiation in this model is then not influenced by the presence of the core and is, in effect, that transferred between infinite parallel faces. In contrast, the present solution is for the case in which all cell surfaces have equal and relatively large emissivities and the core absorbs radiant energy, causing the heat transferred to the cold face by direct radiation to be less than that given by model 2.

The equation for the effective conductivity of model 2 can be derived from equation (8) by assuming a linear temperature distribution and

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$$F_{5,m} = 1 \qquad (m = 1)$$

$$F_{5,m} = 0 \qquad (m \neq 1)$$

in which case equation (8) reduces to

$$\frac{k_E}{k\,\Delta A} = 1 + 3\left(\overline{T}_1 + \overline{T}_5\right)\left(\overline{T}_1^{\,2} + \overline{T}_5^{\,2}\right) \tag{14}$$

Effective conductivities were calculated for the specific cases $\overline{T}_1 = 0.7$, $\overline{T}_5 = 0.5$, and $\frac{h}{S} = 0.8$ and 2.0, and the results are presented in the following table:

Mode of heat transfer	$\frac{k_E}{k\,\Delta A}$ for -	
	$\frac{h}{S} = 0.8$	$\frac{h}{S} = 2.0$
Model 1		
Conduction with linear temperature	1.00	1.00
Radiation with linear temperature	1.26	.69
Total	2.26	1.69
Model 2		
Conduction with linear temperature	1.00	1.00
Radiation between infinite parallel plates	2.66	2.66
Total	3.66	3.66
Present solution		
Conduction	1.35	1.41
Radiation	1.30	.76
Total	2.65	2.17

From a comparison of the results of the present solution with those obtained from the two models, it is apparent that radiation interaction greatly increases the conduction effect. This result occurs because, as previously mentioned, the interaction between radiation and conduction increases the temperature gradient at the cold face.

Model 1, which can be used if the emissivities of all the cell surfaces are equal and relatively large, provides a fair estimate of the effect of radiation but leads to a low estimate of the effect of conduction. From these results, it can be concluded that the interaction effect does not greatly change the amount of heat transferred by radiation.

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Results from model 2 indicate a much larger transfer of heat than that given by the present solution. As a matter of fact, for the examples evaluated, the heat transferred by radiation in model 2 is greater than the total amount given by the present solution. It is also apparent that model 2 provides a better approximation to the present solution as the ratio h/S becomes very small, in which event most of the radiation from the hot side is transferred directly to the cold side. In any case, the effective conductivity calculated for model 2 serves as an upper limit to the solution contained herein.

A comparison of the two cases from the present solution $\left(\frac{h}{S} = 0.8\right.$ and $\left.\frac{h}{S} = 2.0\right)$ shows that in the range of h/S covered in this investigation, the conduction effect changes by only a small amount due to the previously mentioned fact that the temperature distribution is relatively insensitive to changes in h/S.

Comparison With Experimental Results

Previously unpublished results of thermal-conductivity tests performed in the Langley structures research laboratory are shown in figure 6 in which the overall thermal conductivity of an adhesively bonded honeycomb panel is plotted as a function of the average face temperature (the temperature difference between the faces was about 100° F). The panel was made of 17-7 PH stainless steel, and the bonding agent was Shell Adhesive No. 422. The overall height was 0.622 inch, and the face thickness was 0.052 inch. The core density was 6.48 lb/cu ft ($\Delta A = 0.0136$). The cells were 1/4-inch squares.

The tests were performed in a guarded hot plate conforming closely to standards of the American Society for Testing Materials, except that it was designed to test 6-inch-square panels. Since the specimen size was considerably less than that recommended in reference 4, it is likely that the heat passing through the panel was less than the heat supplied by the central heater due to heat losses from the sides of the test specimen. This would cause the experimental values to be too high.

The conductivity of the 17-7 PH stainless-steel core material is as follows:

T, °F	k, $\frac{\text{Btu}}{\text{ft-hr-}^{\circ}\text{F}}$
100	8.8
200	9.25
300	9.75
400	10.2
500	10.65
600	11.15

The above values of conductivity were multiplied by $\Delta A = 0.0136$ to obtain the $k\,\Delta A$ curve shown in figure 6.

If the emissivity of the sandwich material is taken to be 0.8, the effective conductivity due to conduction and radiation k_E shown by the broken line in figure 6 is obtained. Also shown in figure 6 is the conductivity of air k_A. The calculated overall thermal conductivity K shown by the solid line was obtained by adding k_E and k_A at a given temperature and should be compared to the experimental values shown by the symbols.

The difference between theory and experiment could be caused by several factors in addition to the fact that there probably were heat losses from the sides of the specimen resulting in experimental values that are too large. Among these factors are the uncertainty regarding the emissivity and the fact that the local temperature gradient at $\frac{x}{h} = 1$ is greater than the average gradient between $\frac{x}{h} = \frac{5}{6}$ and $\frac{x}{h} = 1$.

CONCLUDING REMARKS

A numerical solution has been made to determine the effective thermal conductivity of honeycomb sandwich panels in which steady-state heat transfer takes place by the coupled modes of conduction and radiation. The calculated effective conductivities can be correlated by the use of a simple dimensionless temperature parameter which involves the face temperatures of the sandwich, the emissivity and conductivity of the core material, and the core height and solidity. Calculated effective conductivities are shown to be in reasonable agreement with experimental values.

Based on the results of the present investigation, the following observations were made:

1. The principal effect of the interaction between radiation and conduction is to cause the temperature distribution in the core to depart from the linear distribution which results from simple conduction theory. This interaction leads to an increased temperature gradient at the colder face and a correspondingly greater transfer of heat by conduction.

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2. The temperature distributions in the core were found to be 5
essentially independent of the ratio of core height to cell size in the 9
range investigated.

3. The interaction between conduction and radiation does not greatly change the amount of radiant-heat transfer calculated by assuming a linear temperature distribution in the core.

4. For given face temperatures and material properties, as the ratio of core height to cell size increases, the effective conductivity decreases due to a lesser amount of heat being transferred to the colder face by radiation.

5. The superposition of heat transfer by conduction with a linear temperature distribution in the core and heat transfer by radiation between infinite parallel plates at the face temperatures of the sandwich results in an upper limit for the effective thermal conductivity given by the present solution.

6. The effective conductivities may be several times greater than the apparent conductivity of a sandwich in which heat transfer by radiation is assumed not to take place.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 27, 1959.

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TABLE I.- OVERALL CONFIGURATION FACTORS

Factor (a)	$\frac{h}{S} = 0.8$	$\frac{h}{S} = 1.2$	$\frac{h}{S} = 1.6$	$\frac{h}{S} = 2.0$
$F_{2,1}$	0.407	0.527	0.620	0.676
$F_{2,3}$	.164	.300	.400	.495
$F_{2,4}$	.092	.133	.145	.125
$F_{2,5}$	.128	.100	.080	.090
$F_{3,1}$	.211	.220	.200	.177
$F_{5,1}$	.252	.152	.100	.040

[a]Equivalent factors are:

$F_{2,1} = F_{5,4} = F_{4,5}$

$F_{2,3} = F_{3,2} = F_{3,4} = F_{4,3}$

$F_{2,4} = F_{4,2}$

$F_{2,5} = F_{5,2} = F_{4,1}$

$F_{3,1} = F_{3,5} = F_{5,3}$

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TABLE II.- CALCULATED EFFECTIVE THERMAL CONDUCTIVITY RATIOS

$\bar{T}_1$	$\bar{T}_5$	$\frac{k_E}{k\ \Delta A}$ for -			
		$\frac{h}{S} = 0.8$	$\frac{h}{S} = 1.2$	$\frac{h}{S} = 1.6$	$\frac{h}{S} = 2.0$
0.2	0.05	1.020	1.017	1.015	1.014
	.10	1.028	1.025	1.022	1.020
	.15	1.042	1.036	1.032	1.030
0.3	0.05	1.060	1.052	1.046	1.042
	.10	1.075	1.065	1.058	1.053
	.15	1.096	1.083	1.074	1.068
	.20	1.112	1.108	1.097	1.088
	.25	1.159	1.139	1.125	1.114
0.4	0.10	1.158	1.138	1.123	1.112
	.20	1.226	1.197	1.177	1.161
	.30	1.332	1.290	1.259	1.237
0.5	0.10	1.290	1.252	1.225	1.204
	.20	1.382	1.332	1.297	1.271
	.30	1.514	1.448	1.401	1.365
	.40	1.697	1.607	1.543	1.433
0.6	0.10	1.482	1.418	1.374	1.339
	.20	1.600	1.522	1.467	1.425
	.30	1.762	1.664	1.594	1.541
	.40	1.979	1.852	1.762	1.693
	.50	2.261	2.095	1.979	1.889
0.7	0.10	1.745	1.647	1.578	1.525
	.20	1.894	1.777	1.695	1.632
	.30	2.090	1.948	1.847	1.771
	.40	2.342	2.166	2.042	1.947
	.50	2.663	2.443	2.288	2.170
	.60	3.062	2.786	2.594	2.445
0.8	0.10	2.092	1.949	1.849	1.771
	.20	2.274	2.108	1.991	1.901
	.30	2.506	2.309	2.170	2.064
	.40	2.798	2.561	2.394	2.266
	.50	3.160	2.872	2.671	2.515
	.60	3.604	3.252	3.009	2.819
	.70	4.139	3.711	3.418	3.185
0.9	0.10	2.534	2.334	2.193	2.085
	.20	2.752	2.523	2.362	2.239
	.30	3.023	2.757	2.571	2.427
	.40	3.357	3.044	2.826	2.656
	.50	3.763	3.392	3.135	2.934
	.60	4.254	3.812	3.508	3.268
	.70	4.839	4.313	3.953	3.666
	.80	5.527	4.904	4.478	4.137

TABLE II.- CALCULATED EFFECTIVE THERMAL CONDUCTIVITY RATIOS - Concluded

$\bar{T}_1$	$\bar{T}_5$	$\frac{k_E}{k\ \Delta A}$ for -			
		$\frac{h}{S}$ = 0.8	$\frac{h}{S}$ = 1.2	$\frac{h}{S}$ = 1.6	$\frac{h}{S}$ = 2.0
1.0	0.10	3.060	2.810	2.620	2.472
	.20	3.338	3.032	2.818	2.652
	.30	3.651	3.300	3.056	2.866
	.40	4.029	3.620	3.344	3.124
	.50	4.482	4.012	3.688	3.432
	.60	5.022	4.473	4.097	3.798
	.70	5.660	5.018	4.581	3.762
	.80	6.407	5.657	5.148	4.738
	.90	7.273	6.398	5.808	5.328
1.2	0.20	4.874	4.360	4.004	3.725
	.40	5.751	5.108	4.668	4.318
	.60	6.955	6.135	5.578	5.129
	.80	8.575	7.518	6.806	6.225
	1.0	10.700	9.335	8.422	7.669
1.4	0.20	6.950	6.148	5.598	5.160
	.40	8.036	7.073	6.418	5.891
	.60	9.478	8.301	7.509	6.862
	.80	11.361	9.910	8.937	8.136
	1.0	13.776	11.975	10.775	9.775
	1.2	16.811	14.576	13.090	11.843
1.6	0.20	9.632	8.449	7.648	6.999
	.40	10.956	9.578	8.650	7.891
	.60	12.664	11.036	9.746	9.046
	.80	14.843	12.898	11.602	10.521
	1.0	17.580	15.241	13.686	12.381
	1.2	20.964	18.140	16.267	14.685
	1.4	25.029	21.669	19.412	17.495
2.0	0.20	17.113	14.862	13.361	12.111
	.40	19.008	16.484	14.805	13.399
	.60	21.344	18.486	16.587	14.988
	.80	24.211	20.940	18.771	16.937
	1.0	27.688	23.920	21.425	19.305
	1.2	31.864	27.501	24.615	22.153
	1.4	36.825	31.757	28.407	25.539
	1.6	42.656	36.762	32.868	29.523
	1.8	49.443	42.589	38.064	34.168

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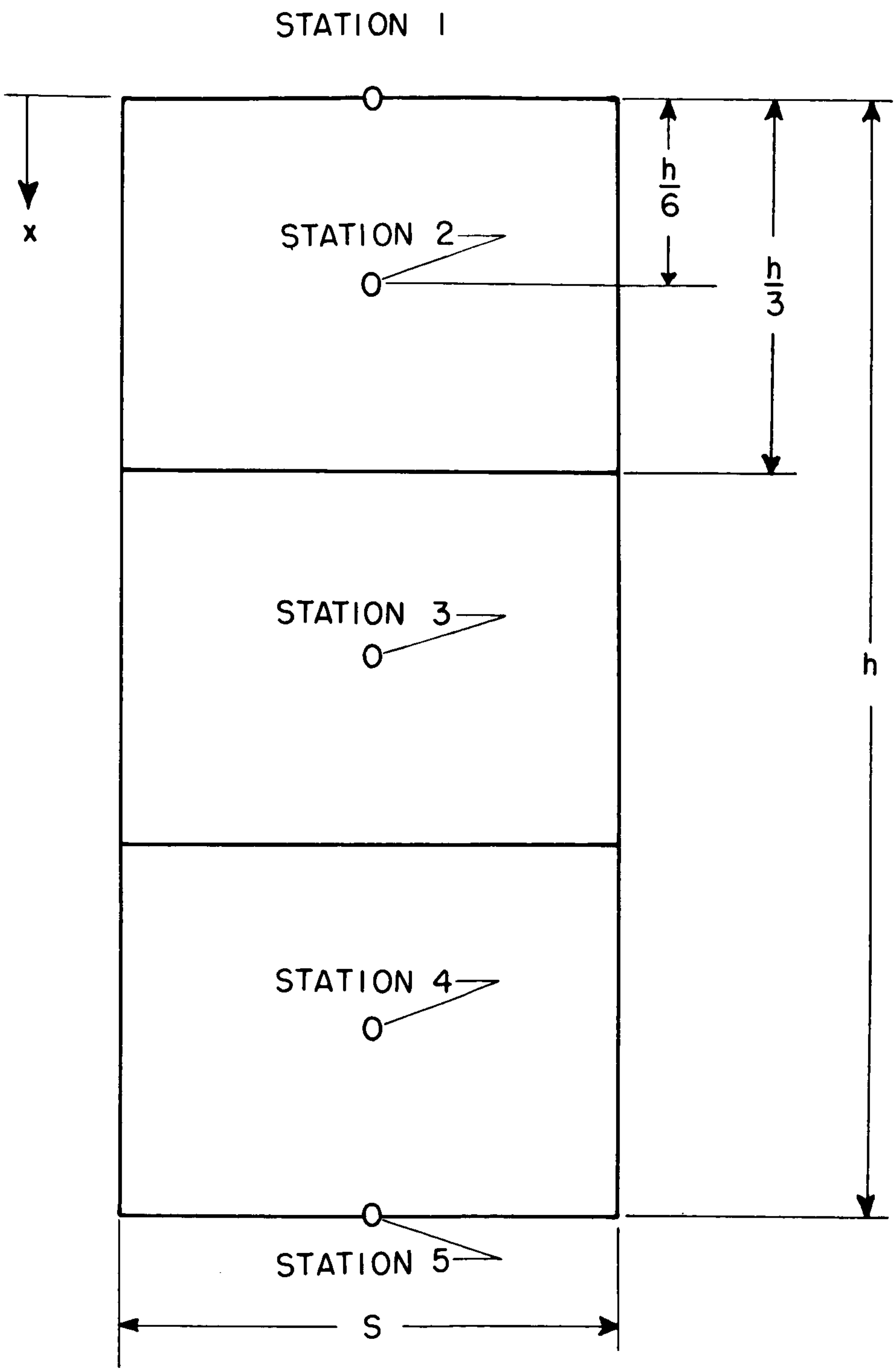

Figure 1.- Side view of square cell showing location of stations used in finite-difference analysis.

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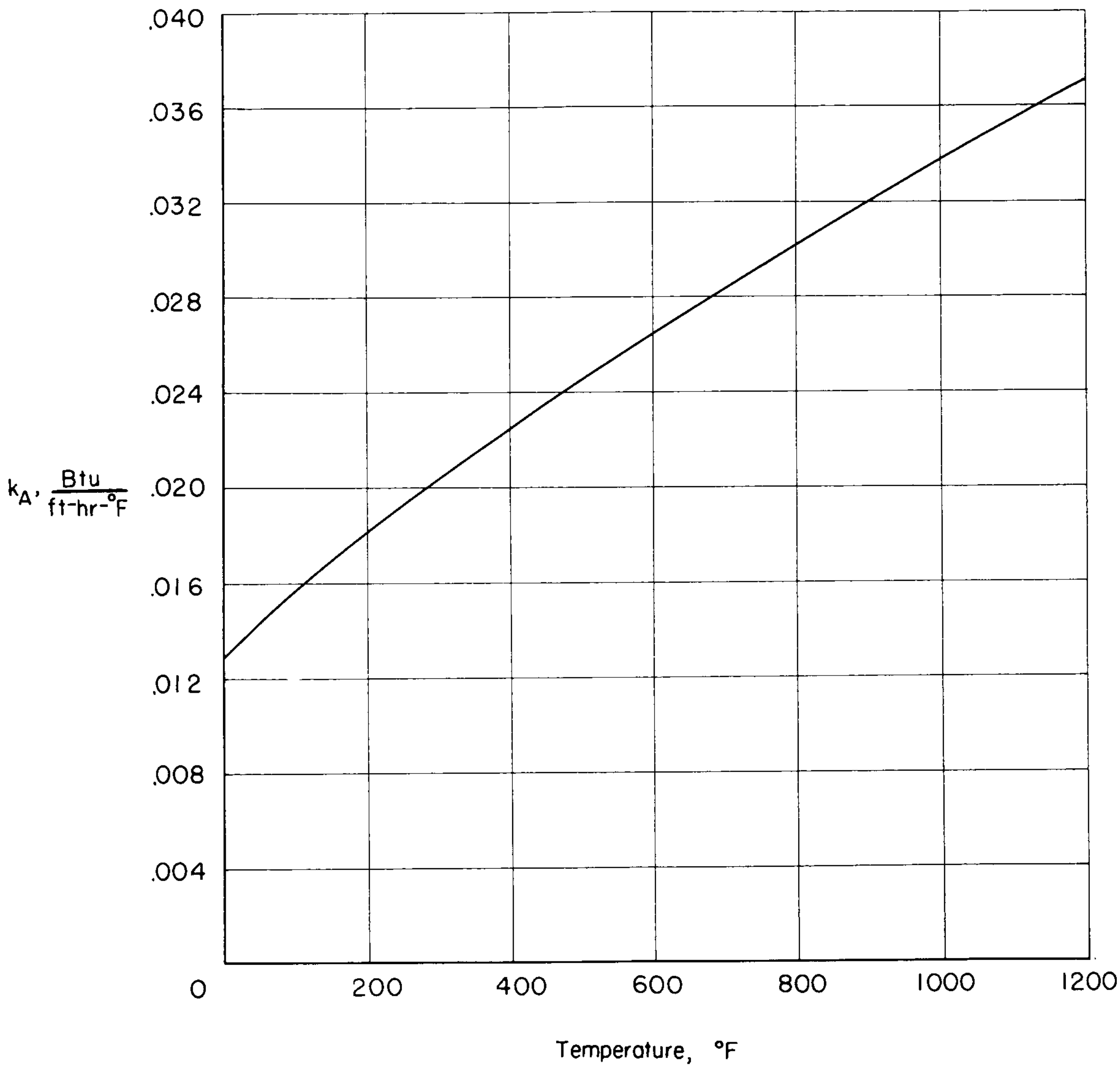

Figure 2.- Thermal conductivity of air.

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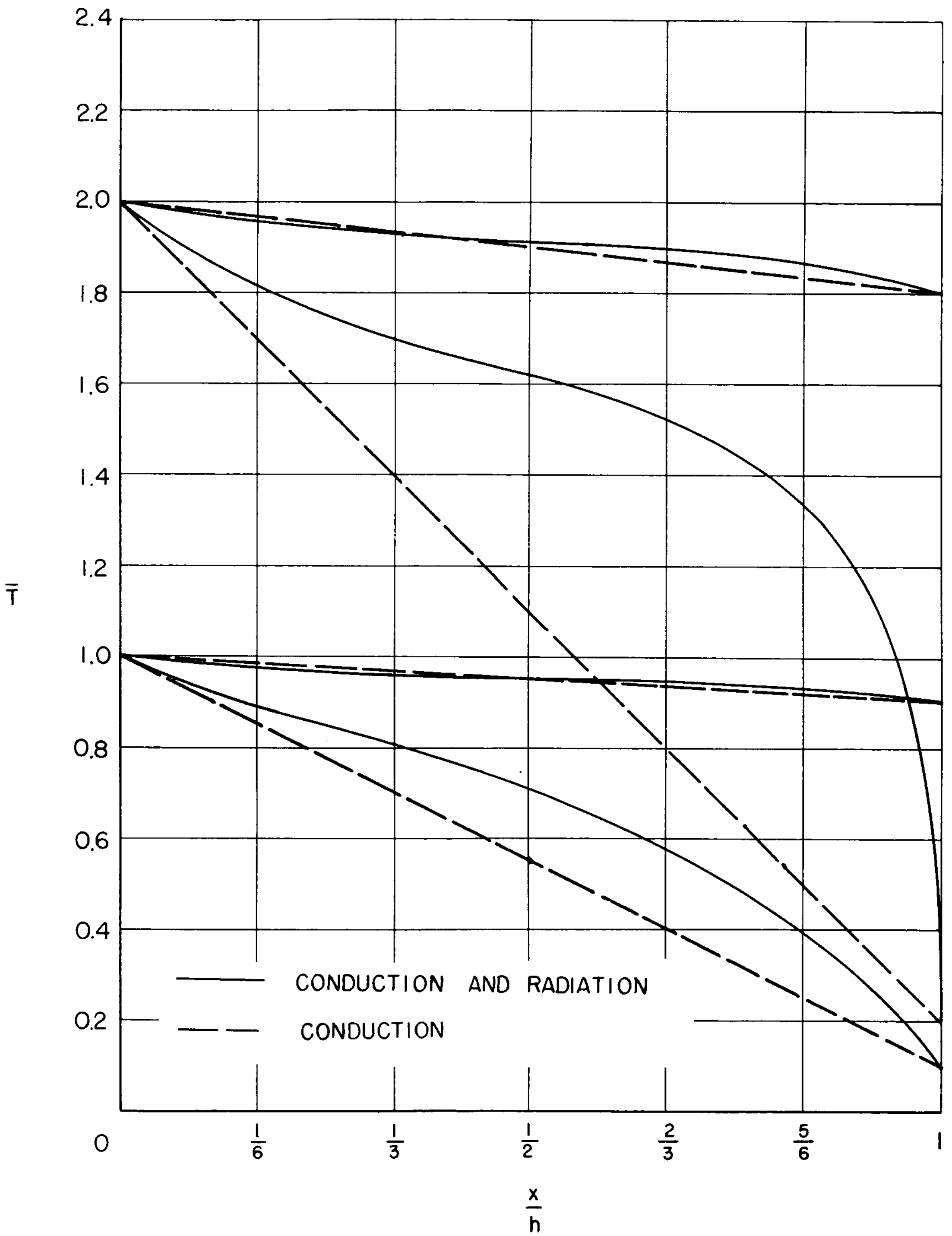

Figure 3.- Typical steady-state temperature distributions through core of square-cell sandwich panel with $\frac{h}{S} = 2.0$.

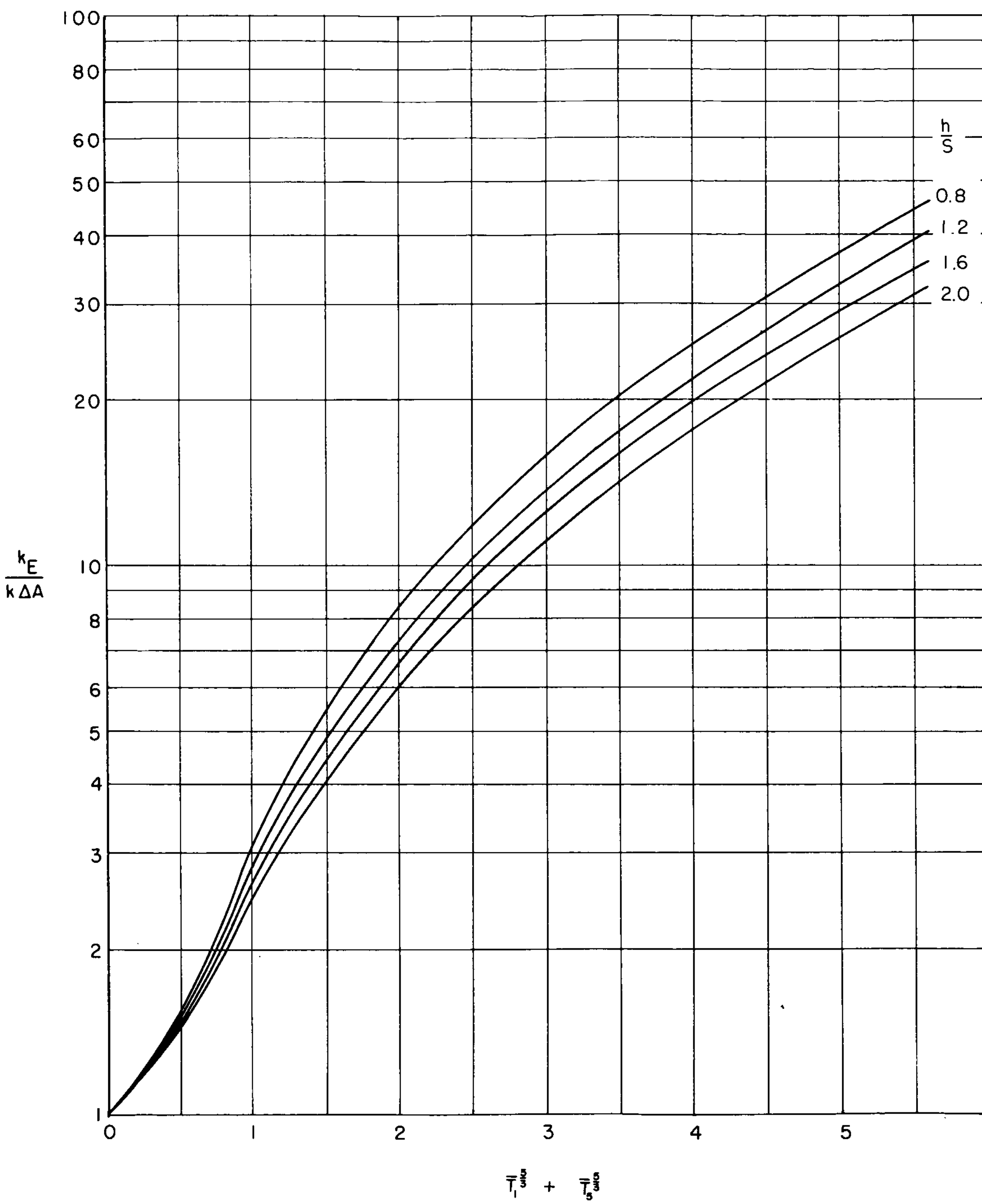

Figure 4.- Thermal conductivity ratio as a function of dimensionless face temperatures.

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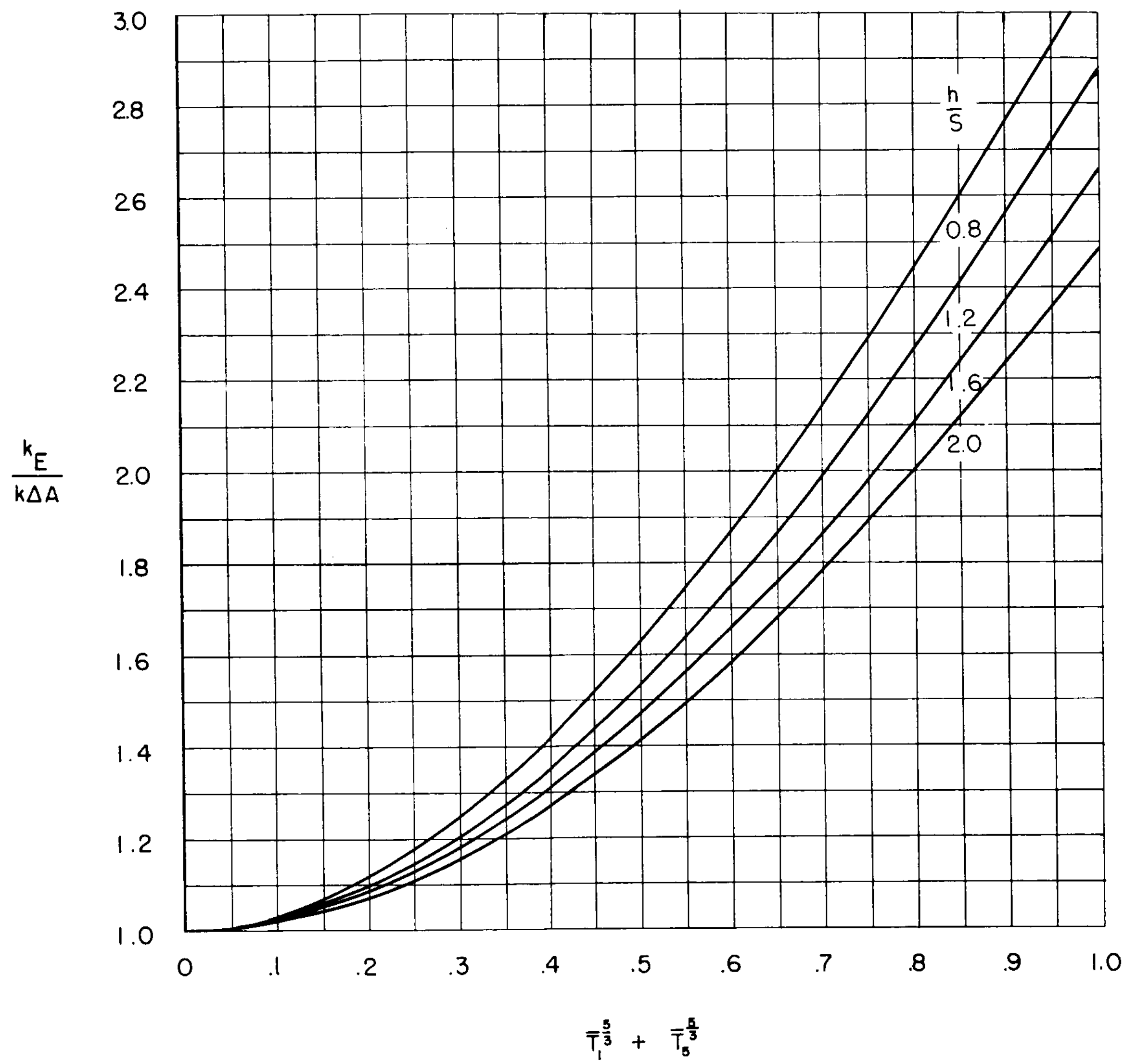

Figure 5.- Thermal conductivity ratio as a function of dimensionless face temperatures with $\bar{T}_1^{5/3} + \bar{T}_5^{5/3} \leqq 1$.

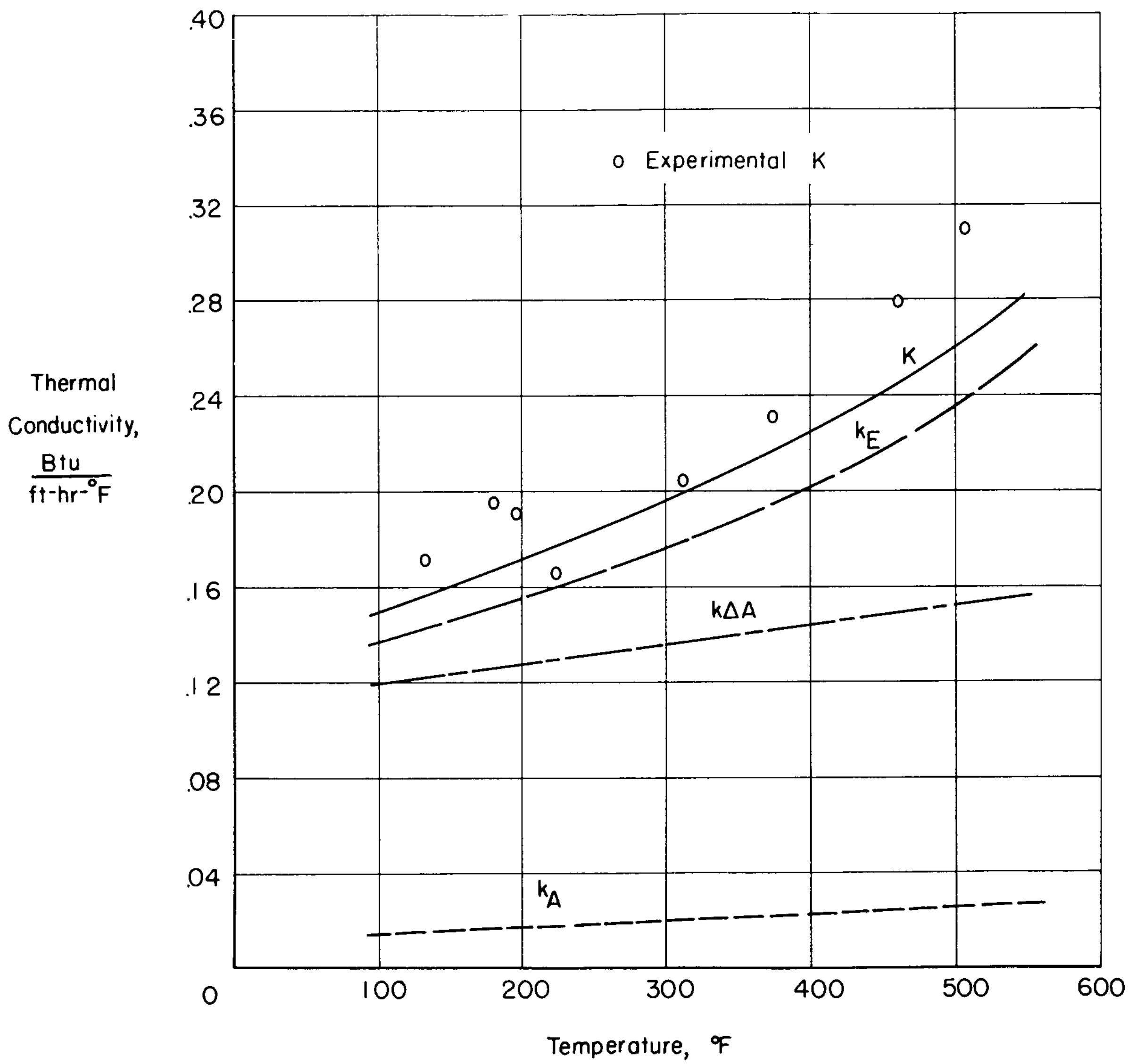

Figure 6.- Comparison of experimental and calculated overall thermal conductivities of a 17-7 PH stainless-steel sandwich panel.